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# Demand Response Service Certification and Customer Baseline Evaluation Using Blockchain Technology

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**ABSTRACT** The use of Distributed Ledger Technologies such as Blockchain for certifying Demand Response services allows for the creation of a distributed system in which customers can communicate with the system operator to provide their flexibility, in a secure, transparent and traceable way. Blockchain technology also supports incentive mechanisms for users taking part in the service through the generation of utility tokens to recognize the user's contribution. This paper presents the experimental test of a novel methodology for Demand Response programs implementation by using the Blockchain technology. The latter is employed for defining a distributed Demand Response service and a new system for its tracing and certification. For this work, a Smart Contract has been conceived and written to execute Demand Response events, calculate users' baseline, compute the support provided by each user towards the fulfilment of the requested load curve modification and remunerate each user with utility tokens proportionally to their contribution. To test the methodology, a Hyperledger Fabric network and a Smart Contract were deployed on four nodes of the Microgrid Laboratory of the Department of Energy Technology at Aalborg University (DK). Subsequently, a realistic scenario comprising two consumer nodes was developed using power electronic converters for generating the household profiles and Smart Meters for the measurement of the consumption profiles. Theoretical and experimental results show the feasibility of Distributed Ledger Technologies in smart grids management with a minimum investment in new hardware while enabling the active participation of customers in Demand Response more transparently and fairly.

**INDEX TERMS** Blockchain, demand response, distributed balancing, baseline, hyperledger fabric, smart contract.

## I. INTRODUCTION

Recent potential applications of the Blockchain (BC) technology to the power systems sector are devoted to Demand Response (DR) management, as it represents an efficient solution to respond to power fluctuations due to the penetration of Renewable Energy Sources (RES) in the electrical system. DR is a structured program of actions that can be performed by the final user (industrial, commercial or residential) to modify the electric load diagram (lowering it, increasing it or shifting it horizontally) in response to problems in the network, such as network congestion, temporary unavailability of power caused by failures or intermittent production from non-programmable RES, or in response to the dynamics of wholesale electricity prices [1]. One of the main issues in the provision of flexibility service through DR programs is the lack of transparency and the large information asymmetry towards end users. A good number of papers in the literature handle these issues using Distributed Ledger Technologies (DLTs). The recent H2020 project DELTA [2]

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proposes a Virtual Node (VN) Platform that aims to face the challenge of peak loading and unbalance through end-users cooperation and interactive behaviour. The VN is defined as a layer between customers and the aggregator, which clusters users sharing specific characteristics for flexibility provision. VNs are equipped with a multi-agent system that creates and updates energy profiles for each customer in the aggregator's portfolio, with load forecasting and dispatch optimization tools that provide the necessary information required for self-balancing and preventing the internal loss of energy or stability [3]. In order to automate asset handling, calculate aggregated energy and automate various time-consuming workflows, a new device called Fog-Enabled Intelligent Device (FEID) is used. However, the project is still running, so it is not clear yet, how it will interact with the currently available technologies as it seems far from a real-world application. Moreover, no new publications, except proof of concept papers, are available at this stage about the project [3]. The literature also shows some other studies that approach the DR problem with the use of DLTs. In [4], the authors explore the application of BC technology to Demand Side Management (DSM) while facilitating Machine-to-Machine (M2M) interaction. Data derived from power flow calculations are recorded in the BC, where a Smart Contract (SC) is used to customize the data and to automatically transfer assets. The paper [5] proposes Virtual Machine (VM) environment tests using Multichain. However, the use of Multichain does not support SCs. Other interesting works [6]–[8], propose new systems to provide energy flexibility services to system operators (TSO or DSO) through DR actions based on BC technology, but considering only the interaction between system operators and Balance Service Providers (BSP) without taking into account how prosumers operate the load variations. These works propose to integrate BC solutions in the currently existing DR programs with the aim of reducing information asymmetry for the customers. In [9] the use of BC technology is considered for exploiting energy flexibility timely through the adaptation of energy demand profiles of prosumers. An Ethereum [10] BC stores energy prosumption information collected from IoT devices, while self-enforcing SCs define the expected energy flexibility at the level of each prosumer, the associated rewards or penalties, and the rules for balancing the energy demand with the energy production at the grid level. While the experimental section only shows VMs implementation, a public BC like Ethereum does not seem adequate to support an environment, i.e. the electricity market, as consensus mechanisms could be too burdensome and management more complex.

### *A. CHALLENGES IN THE IMPLEMENTATION OF DEMAND RESPONSE PROGRAMS*

DR programs are a set of activities with the aim of optimizing energy consumption in specific time intervals, namely DR events. SCs are software programs that are executed in a distributed way and automatically execute when specific pre-defined conditions occur.

DR programs are currently implemented by means of centralised communication architectures, in which data and operation logic over data are managed by a single entity. In current Demand Response programs implementations, an aggregator takes care of sharing the load modification burden among the end users according to a logic and based on data that are not transparent to end users and neither to the grid operator who requested the modulation service. On the other hand, highly stochastic behavior of generation units on the grid will ask for more flexibility of energy resources in the system and thus for further involvement of end-users. Such variability, has increased the need for balancing services and close to real-time markets. This can be managed by means of a suitable technology that handles transparently and with limited delay the communications between end users and aggregators, when the request of modulated power from the latter suitably accounts for high variability supply and demand. However, as emerges from the report [11], [12] about real world practices in this area, end users are rarely involved in demand response programs for ancillary markets for primary regulation and if so, they only provide some capacity to be activated by directly turning on/off the loads, such as it happens in Finland and UK with heating electric loads. More frequently, end users can take part to secondary and tertiary regulation. As already seen by the literature review above, Demand Response programs can be implemented using Distributed Ledger Technologies and in particular BC platforms. The use of BC platforms for DR services provision, while providing transparency, information symmetry and security to those who take part to the platform, entails some challenges that are detailed below.

The new General Data Protection Regulation (GDPR) requires the existence of one liable party and one entity, the Data Controller, "natural or legal person, public authority, agency or another body, which, alone or jointly with others, determines the purposes and means of the processing of personal data" [13]. The compliance with GDPR with respect to this issue calls for the use of permissioned BC platforms. BC platforms are indeed currently deployed as permissioned and permissionless [14]; permissioned BC needs prior approval from one entity before taking part to it, whereas permissionless BC lets anyone participate in the system. In permissioned BC, the identity of participants is known in permissionless BC, participants are anonymous. Another important difference concerns the complexity of the algorithm that guarantees the correctness of the data stored in the BC. Permissioned BC uses lighter consensus algorithms, while the permissionless one uses heavier computational effort, as well as the so-called "Proof-of-Work" (PoW) algorithm [15]. Another relevant issue for the use of BC in cyber-physical energy systems is the compliance of the platform with the metering infrastructure, DLTs must indeed be complemented with a suitable metering infrastructure in place. Another challenge in using the BC for DR certification concerns the timing of transactions implementation. Using permissionless BC ensures greater security, but, due to the computation time of the underlying mining algorithms, is not adequate for managing close to real time operations. For this reason, a more adequate choice concerns the use of a permissioned BC for energy related applications and, in particular, DR programs implementation. The Third Energy Package of the European Union [16], already in 2009, required all Member States to ensure the implementation of intelligent metering systems for the long-term benefit of consumers. Such intelligent metering systems are usually referred to as Smart Meters (SMs). By SMs, consumers should also be able to access dynamic electricity price contracts. The report from the Commission *Benchmarking Smart Metering Deployment in the EU-27 with a focus on electricity* sets targets for the massive roll-out of SMs: 72% of end-users in EU-27 are expected to have SMs by 2020. Such as in most member states, in Italy, the implementation is carried out by the Distribution System Operator (DSO).

The Directive from the EU parliament on common rules for the internal market in electricity identifies two drivers. The first driver is allowing DSOs to manage local flexibility resources. In this way, network costs could be significantly reduced. Another key driver to competition and consumer engagement is information. Previous Commission consultations and studies have shown that consumers complain about a lack of transparency in electricity markets, thus, reducing their ability to benefit from competition and actively participate in markets. Consumers do not feel informed enough about alternative suppliers or the availability of new energy services. They also complain about the complexity of offers and procedures for switching suppliers. The reform will also ensure data protection as increasing use of new technologies (notably smart metering systems) will generate a range of energy data, carrying high commercial value [17].

However, current SMs are not sufficiently ''smart'' from a distributed architecture perspective. The ''smartness'' of the metering infrastructure basically refers to the possibility for a DSO to read the metering data remotely and eliminating the need for customer consumption estimations of consumption. Moreover, they can provide the metered data directly to the customers through a dedicated local channel.

The SMs for the Italian electric energy market are an exemplary case. In their 2.0 release (SM2G), they present two separate channels of communication. The first channel is directed towards the central distribution system (*chain 1*) for exchanging information with the DSO and validated data with the retailers. The second channel (*chain 2*) is directed towards any local home automation system for more intelligent management of consumption at home, but it provides non-validated data. The *chain 1* allows for real-time communication using the A-band PLC technology, while the *chain 2* uses the C-band PLC that provide the same or better performance than the A-band PLC as it is subject to minor disturbance [18]. The lack of connectivity between SMs and the Internet and the impossibility to install customers' code on them for security reasons, hinders the possibility to use them as nodes of the BC. This is currently not possible and creates some problems when it comes to open the market to third parties who could manage the BC platform.

The same situation can be found in other member states such as Denmark, whose SMs deployment status has reached almost 100%. Danish smart metering infrastructure follows a philosophy similar to the Italian one with a local communication channel where the customer can incorporate in-home displays or monitoring systems, and an external channel sending data to the DSO's concentrator. In the Danish case, RF proprietary standards or Wireless M-bus are commonly used between the SMs and the data concentrators, while the local interface is usually provided with a serial port where Internet-based communication modules can be attached. This increases the flexibility of the system compared with the Italian case but is still not enough to directly support BC applications [19].

In this paper, it is defined and presented a blockchain-based platform that uses the Advanced Metering Infrastructures (AMIs) at the Aalborg University, specifically in the Microgrid laboratory, and demonstrates how the use of SCs is suitable for defining and implementing DR programs. The experimental part of this paper aims to demonstrate the technical feasibility of implementing DLTs and in particular a permissioned BC technology in smart grids, to further enable customers participation in the DR mechanisms and improve transparency in users' remuneration for their contribution to DR programs. In particular, a new method for the certification, remuneration and optimization of the DR programs is outlined and implemented. The experimental approach proposed in this paper solves the above raised challenges of current DR platforms:

- improves information asymmetry;
- guarantees data security;
- can put the basis for future disintermediation.

At the same time, the proposed approach overcomes the listed challenges of blockchain platforms for DR:

- is compliant with GDPR by means of the use of a permissioned blockchain platform and the provision of organisations for restricting the access to personal data;
- is scalable and allows participation of end users to real time markets, due to the lighter consensus algorithms of permissioned blockchain;
- compensates the insufficient ''smartness'' of available SMs.

The main contributions of the paper consist in:

- Experimental development of a laboratory scale hardware-software test bed for blockchain based DR programs platforms testing.
- Development of a Blockchain based platform for DR service certification and CBL evaluation. In details, the implemented functions are: measurements acquisition; CBL calculation; reward functions evaluation.
- Design and implementation of a dedicated SC for the above functions execution.

The paper is structured as follows. In Section II, a review about DR strategies is provided as well as a comparison of

BC technologies with current dedicated protocols for managing DR programs. Section III explains the methodology used for the system developed. While in the last section the experimental setup used for the tests and the results obtained are described.

## II. DEMAND RESPONSE AND BLOCKCHAIN FOR DEMAND RESPONSE

### A. DEMAND RESPONSE STRATEGIES

As unpredictable renewable energy generation increases in power systems, mismatches between production and consumption are more likely to occur. This implies various technical and market consequences, such as congestion of the distribution networks, peaks in energy prices and ultimately the curtailment of renewable energy plants. One of the cheapest solutions for operating the system in order to deal with these problems is implementing DR programs. In a nutshell, the term ''DR'' refers to any program that encourages end users to take actions in order to shift or modify the energy consumption profile. The actions can be performed directly by specialized operators, called Balancing Service Providers (BSP), or by end-users who decide to act either independently or on the basis of information (almost) in real-time [20].

DR programs are thus designed to encourage the end users' participation, and their response to prices is essential to get efficient and competitive market and technical outcomes. It was proved that for wholesale electricity markets, as for any other kind of market, the more the demand actively participates, the more competitive and robust the market becomes [21]. DR programs remunerate end-users of electricity for agreeing to modify their consumption for a specified amount of time. Aggregating many electricity users together can amount to substantial control over demand, giving system operators new ways to balance the grid [22].

The benefits of DR are known in the literature, because by shifting and appropriately lowering the peaks of power demand, the use of generation systems with higher marginal costs would be less needed. As a result, the costs associated with congestion would decrease, less investments would be needed for the transmission and distribution networks, and sector competition in liberalized markets would be stimulated. In the same way, if a renewable generation plant injects electricity when loads are low, an increase of electrical load in some other periods can avoid the curtailment of such sources, thus, reducing the associated economic losses.

DR can be generally implemented acting on two tunable knobs: capacity and balancing [22]. The purpose of working on capacity is to moderate peak electricity demands, so customers participate in the program by making their own load capacity available. The peak demand happens only a few times per year and can be mitigated, without DR, building new generation capacity. At residential level it is possible to shift some loads or reduce them [23], although it can have an impact on user comfort. In addition, since it is based on low energy consumption appliances, an aggregator is needed to participate in the energy market. In this way, there is no need to build new expensive power plants for facing the peaks and customers can receive economic benefits by meeting the DR requests [24], [25].

The second category, DR as balancing, has the purpose to balance in an automatic way predictable variation in renewable energy output. Using this kind of DR, grid operators can directly regulate the use of customers' electricity so as to cope with the rapid change in production from renewable sources. Therefore, with DR as balancing, it is possible to match the production from renewable sources by adjusting the demand in real time, to reduce energy price as it rewards the consumption from renewable sources and avoids renewable sources curtailment. Moreover, it provides grid operators a tool for regulation services and, finally, creates a revenue stream for consumers. The final objectives of these two kinds of DR can be reached using different programs as depicted in Fig. 1 [1], [23], [26].

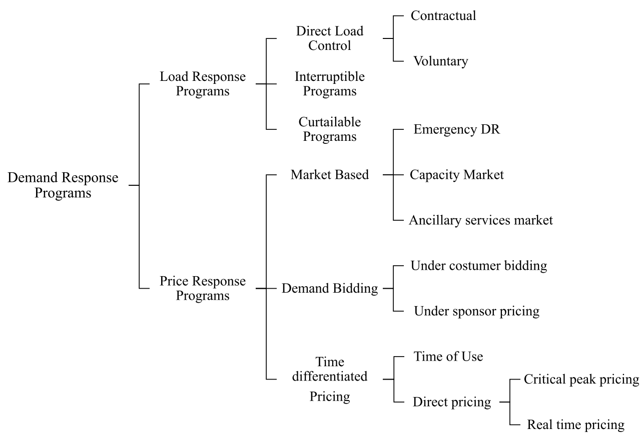



**FIGURE 1.** Classification of DR programs.

As shown in figure 1, the DR programs can be divided into two main categories:

- Load Response Programs.
- Price Response Programs.

In the load response programs, participants receive incentives or reduction in bills by reducing load when the utility asks them to do so. On the other hand, the price response programs, widely used for industrial, commercial and residential customers, offer an economic incentive for taking part to the program.

Another classification can be carried out according to how load changes are brought about. From this point of view, two categories are distinguished:

- Price-based DR.
- Incentive-based DR.

The first refers to changes in use by customers in response to changes in the prices paid. The second offers incentives to customers for a modulation of the demand; these incentives can either be separate or additional to retail electricity. Some DR programs penalize customers who sign up but do not respond or do not fulfil their contractual commitments when events are declared [27].

The application proposed in this work implements an incentive-based DR program and can be considered as an implementation of load response programs both for capacity and balancing. Loads are controlled directly, and customers can act on a contractual basis, since they are remunerated in response of a measurable action of turning on/off or shift one or more loads. In this case, the transparency provided by the blockchain can strengthen trust and thus incentivize the participation of end-users to DR programs. Moreover, incentives are supplied to end users based on the service offered to the grid from time to time.

### B. BC TECHNOLOGIES VERSUS OpenADR

BC technology can be considered one of the most promising technologies of the twenty-first century. Introduced in 2008 with Bitcoin [28], today, there are many use cases and several research studies on that exploiting and exemplifying its use. The reason is probably its advantages compared to other DLTs. In general terms, BC can be defined as an append-only distributed ledger of transactions updated after a validation process (called consensus), which is structured in blocks and maintained by network nodes. Each block is linked to the previous one using particular cryptographic functions called *"hash functions"* [29], therefore, the modification of a single bit within a block involves the modification of the whole chain [30], see Fig. 2.

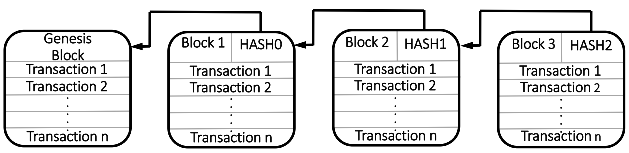



**FIGURE 2.** **Implementation of BC blocks.**

Before the advent of BC, transactions of any good were recorded in centralized databases and managed by a trusted authority. For example, in the financial field this central role is run by the bank, in the energy world by the system operators (i.e., DSO or TSO). So, the first novelty introduced by the distributed architecture based on the BC is the decentralization of trust and the solution of some problems afflicting decentralized systems [31], [32]. Using the distributed architecture, each node can see, control and approve all transactions and is part of a network that allows for the traceability of all transactions. In turn, it is also an archive for all transactions and, thus, for the history of each transaction that is available on all the nodes of the network and immutable (unless the same modification is applied in the whole network and only after the approval). The BC was proposed to be used for attributing power losses of the distribution network to the users [33] and for managing ancillary services [34]. Furthermore, several possible applications and related challenges has been foreseen for the near future [35]. The use of the BC technology allows for:

1) *Transparency*, because each block added to the BC is accessible to all participants and is in the archive of all participants;
2) *Trust*, based on cryptographic functions, which allows the BC to work in distributed and unreliable environments;
3) *Immutability*, since a block, thanks to the use of hash functions, once added, can be changed only with the approval of most of the participants in the network;
4) *Confidence*, since there is a shared reading among all the participants;
5) *Efficiency*, since it requires no intermediaries than the classic transaction management system, thus simplifying processes, infrastructures and increasing operational efficiency;
6) *Control* and *security*, since it allows the use of cryptography allowing greater data protection and lower risk of fraud.

Last but not least, features of the BC include the possible reduction of the transaction costs, due to the direct exchange of assets between network users without intermediaries (if we consider private BC without mining process [30]) and the possibility of using SC [36] to automate the transactions execution, thus, allowing rapid and safe exchanges. A SC can be defined as a self-executing contract with the terms of the agreement between the two parts being directly written into lines of code contained in the BC. Most part of the DR programs are today implemented as centralized systems: decisions on loads control are taken by the system operator or aggregator based on dynamic programming optimization [37], fuzzy logic-based decisions [38], or other profit maximization schemes [39], [40], and proposed to the customers. This stems from information asymmetry and centralized control over available information deduced by smart metering devices. Even when a decentralized dispatch based on price signals affecting the user decisions [41] is implemented, prices are decided in a centralized way. Recently, other logically decentralized P2P architectures have been proposed [42].

In this work, the decision logic is distributed and cooperative, but the storage of data and the validation of measures and of the logic itself are still centralized. However, it will be shown that the design choices that appear as limiting the BC potential, on the other hand, reproduce a realistic scenario, where all market actors are represented and take part. Essentially, DR systems are mostly based on a classical client–server service architecture, where a server keeps the links with industrial or residential customers for collecting measures and issues control signals. The most applied protocol to exchange information and signals in DR contexts is the Open Automatic DR, Open ADR [43]. The latter is an open access protocol that is implemented on a client server architecture and uses HTTP for transport implementation, while Public key cryptography ensures security. The use of BC for DR as compared to OpenADR client server guarantees two main benefits:

- Transparency over measures and pricing mechanisms;
- No single point of failure.

Fig. 3 shows a possible abstraction of the two communication models. As it can be seen, BC technology relies on several layers: the P2P network layer is responsible for inter-node communication, discovery and data transfer (usually transactions and block propagation). The consensus Layer includes code required to generate the order of blocks creation and validate blocks created by other nodes in the network. The virtual machine layer is a ''transactional engine'', responsible for changes in a BC's world state. The fourth BC abstraction layer consists of two ''branches'': Application Programming Interface, API, used by on-chain applications in runtime, and programming languages, used in development time and compiled for runtime into a binary code that can be put into BC and understood by the VMs. The language level refers to the SC development language. Starting from the Application business (on chain and off chain) layer, the code is usually written by third-party developers and not by core BC teams. In fact, these are application-specific projects that utilize the underlying BC in order to deliver some vertical solutions. The final layer is the actual User Interface, UI, of the dApp presented to the user [44].

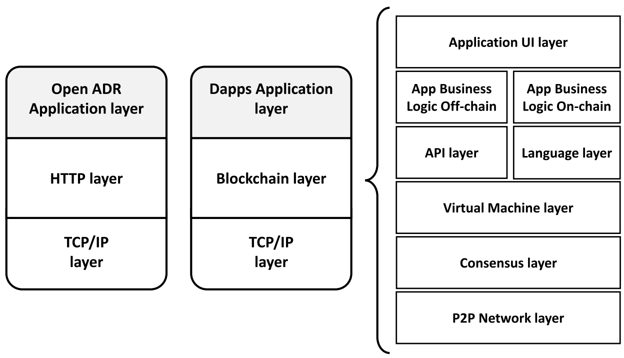



**FIGURE 3. Abstraction model for OpenADR and BC.**

## III. METHODOLOGY

### A. INTEGRATION OF THE BC TECHNOLOGY INTO THE POWER NETWORK ARCHITECTURE

The proposed BC-based platform has been set up for DR programs implementation. The system has been developed considering the possibility of integration with existing technologies generally used for the low voltage grid. Considering a microgrid consisting of consumers and prosumers and considering the use of second generation SMs, Fig. 4 shows the proposed architecture. The permissioned BC-based solution for handling DR operations is developed using an Hyperledger Fabric network. In this architecture, measures are collected from the external channel of the SMs and sent to the data concentrator, the same measures are sent by the retailer to the BC. The data concentrator may appear as a single point of failure of the network, however, in general, it is not. In fact, several concentrators could be deployed to serve districts or local areas. Concentrators require the computational power to act as BC clients and off-the-shelf embedded devices are sufficient for this goal. Additionally,

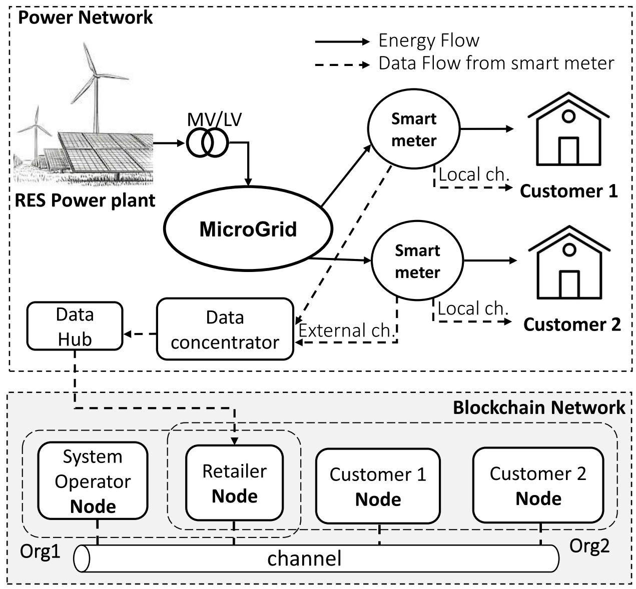



**FIGURE 4. Proposed BC-based architecture.**

customers have the potential to deploy their own clients, reading data from the smart meter and checking whether they match those registered by the retailer on the BC. In such a case, consumption data is both provided by the retailer on the BC and by using the local channel of the SM. The aggregating device (data concentrator in this case) solves the problem of direct connection of the current SM to the BC and provides a data-flow that is trusted for the customer permitting further validation by checking the matching with data coming from the retailer and the distributor. The BC users, through a client application, invoke a dedicated SC for elaborating, in a distributed manner, the transactions logic. Moreover, the SC invoked by the system operator asking for the DR service computes the baseline for each user by reading the measurements registered on the BC. In a nutshell, the SC is the element that allows to implement the DR service in all its parts, from recording customer load profiles on the BC, to event execution and customer remuneration.

This architecture can be perfectly integrated with the existing market model for DR, giving a role to the existing actors. What is here called system operator is the entity requesting the DR event, while the 'retailer' is the entity receiving the measures from the data concentrator collected through the SMs and is responsible for the energy billing.

#### 1) HYPERLEDGER FABRIC NETWORK

Hyperledger Fabric is a BC with highly modular and configurable architecture, which allows for innovation, versatility and optimization in a wide range of use cases. As already mentioned, Fabric platform is a permissioned BC, which means that the participants are known to each other rather than anonymous [30]. Instead of being an open and permissionless system that allows unknown identities to participate in the network (requiring computationally expensive consensus protocols such as PoW to validate transactions and secure the network [15]), Hyperledger Fabric members are registered through a Membership Service Provider (MSP) of trust. The direct consequence of the non-use of consensus protocols like the PoW, and therefore the lack of mining operations, is the reduction of costs for the execution of transactions.

Hyperledger Fabric is also the first BC platform to support SC, called "chaincodes", written in generic programming languages like Java, Go and Node.js [45]. A SC is a code that implements a shared logic supporting the transactions and managing access and modifications to a set of key-value pairs in the "current ledger state". This important feature makes this BC an easy-to-use tool for a wide variety of distributed applications. In this work, we used Go language for the development of the DR SC. The Hyperledger fabric BC is based on a particular modular architecture that logically arranges the components of the node, and then of the network, into different containers. Fig. 5 shows the main modular components of the Hyperledger Fabric network.

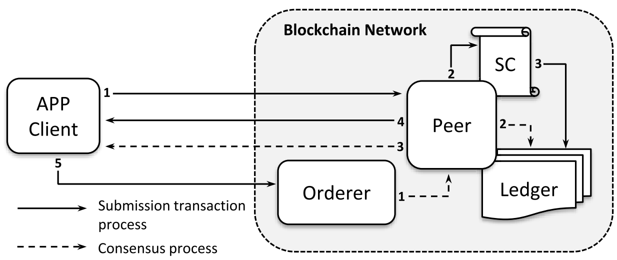



**FIGURE 5.** **Main components of a single node Hyperledger fabric network.**

As it is shown in Fig. 5, the elementary network consists of five components: a Peer, a SC, a copy of the ledger, an App client and an Orderer. The peer is the fundamental element of the network because is the entity that maintains the copy of the ledger and hosts and runs the SC in order to perform read/write operations to the ledger. Peers are owned and maintained by members of the BC network. The App client, external to the BC network, is the necessary element to communicate with the peer and shows to the members (end-user or administrator network) the results following a query or a "transaction proposal". The solid line arrows of Fig. 5 show the process of execution and diffusion of a transaction. The network member, through the App client, signs the "transaction proposal" and sends it (1) to all peers participating in the BC. Each peer receives the signed transaction proposal and invokes the SC (2) calling up a function that interrogates the ledger (3) and generates a "proposal response". The proposal response signed by all peers are sent to the App Client of the user who submitted the transaction proposal (4), that checks the signatures of all peers and compares the replies of the proposal to determine whether they are the same. If they are the same, you can proceed to the next step. If the transaction proposal is a simple query, it is not sent to the Orderer but directly displayed by the App Client of the user who submitted the transaction proposal. If the transaction proposal implies instead a change of the ledger status, after comparing the correspondence of all the answers obtained by the peers, the App Client sends the response within a "transaction message" to the Orderer (5) that is the component responsible for the consensus process. The transaction message will contain the transaction data and peers' signatures. The Orderer does not need to inspect the entire content of a transaction to perform its operation, it simply receives the transactions, orders them chronologically and creates transaction blocks.

Transactions must be written to the ledger in the order in which they occur, even though they occur involving different groups of participants in the network. In order for this to happen, it is necessary to establish the order of the transactions and create a method to reject the erroneous transactions that were entered in the ledger by mistake (or maliciously). This task in Hyperledger Fabric is entrusted to the Orderer.

The dashed line arrows of Fig.5 show the update process of the ledger after the consensus process performed by the Orderer. Once the transactions order has been established, the new transactions are sent to the peers in blocks (1), the peers update the ledger with the new transactions block (2) and, to conclude, the peers send to the App Client a message (3) to communicate the updating of the ledger. Another important feature of Hyperledger Fabric compared to other BC is the possibility to choose the consensus protocol that best represents the existing relationships between the participants. Until version 1.0, there are two consensus mechanisms available, namely, SOLO and Kafka. SOLO is the simplest mechanism, which only broadcasts the transaction without establishing any real consensus. Clearly, it is not recommended for production. On the other hand, Kafka uses a fault-tolerant distributed streaming platform called Apache Kafka [46]. It also enables distributed ordering service, so that we can have multiple Orderer nodes to avoid a single point of failure [45], [47]. In addition, the consensus protocols of Fabric do not require a native cryptocurrency to incentivize expensive mining activities or to fuel the execution of SCs. The absence of cryptographic mining operations allows the platform to be distributed at the same operating cost as any other distributed system. The combination of these features makes Fabric a very performing platform in terms of transaction processing and transaction confirmation latency, and provides privacy, transaction confidentiality and the implementation of SCs [45].

In our application, to test the network, we used only one Orderer and SOLO consensus mechanism because the aim of the work is to show the possibility of integration of the BC system with the existing technologies and the development of a new certification system for the DR. In the upcoming work, the system will also be tested with different consensus mechanisms, thus affecting computation times.

Regarding privacy within the BC network, Hyperledger Fabric allows choosing three different solutions. The first consists in the use of communication mechanisms, called "channels", which allow for data isolation and confidentiality and by which the peers can communicate with each other. On a specific channel, the ledger is shared across the peers taking part to that channel, and transacting parties must be properly authenticated to a channel in order to interact with it. Hyperledger Fabric offers the possibility of creating different channels on the same network, allowing a group of participants to create a separate transaction ledger. If two participants form a channel, these two participants, and no one else, have copies of the ledger for that channel preserving the privacy and confidentiality of both. All members of Hyperledger Fabric BC are usually grouped into organizations and multiple organizations can be grouped into consortia. An organization can host more than one peer and client. Starting from version 1.2, in order to preserve the confidentiality of data on the network without creating different channels, Fabric offers a second solution creating "private data collections", which allow a defined subset of organizations on a channel to support, commit or query private data without having to create a separate channel [48]. The last solution consists in the use of attributes included inside the digital identity of the network's members to determine permissions to use different functions implemented by the SC.

In this work we consider two organizations. The first organization (Org1) is composed of the system operator and the retailer, while the second (Org2) is composed of the retailer and the customers (see at the bottom in Fig. 4). The identities of all the members of the network are encapsulated in an X.509 digital certificate and they are certificated and verified by a MSP. We considered two Membership Service Providers, MSP, one for Org1 and one for Org2. So the MSP of Org1 is managed by the system operator and is needed to verify the identity of the retailers, while the MSP of Org2 is managed by the retailer and is needed to verify the identities of the customers. Even if the SC is the same for all peers and can be viewed by all users participating in the CB, using the attributes we determined the permissions to access the different functions implemented by the SC and we manage the privacy among the various network users [49]. Using this solution each customer can read from the BC only those data that concern him, such as his own baseline, his own consumption or earned tokens, but he cannot read any data related to another customer.

### 2) SMART METERING SYSTEM

In this work, we assume that the SMs are owned and operated by the DSO (system operator), while the billing is managed by the retailer. This is the most frequent scenario among the EU Member States. The DSO uses the acquired information for both managing the network (e.g., controlling network losses) and providing retailers with validated data to be used for billing. Then, the DSO collects the measurements and makes them available to the retailer through the so-called "data management hub". This dataflow has the main goal to provide suppliers with validated consumption data for billing. The validation process ensures that collected data are sufficient and consistent for the billing phase using advanced data reconstruction algorithms [18]. The community shown in Fig. 4 is operating as a microgrid that is able to exchange energy with the grid, but each customer has a different consumption pattern, so an individual SM is needed for each customer. We used 3-phase Kamstrup OMNIA meters, very employed in Denmark. The load profiles of the customers are sent by the SMs to the data concentrator through the external channel. The communication between the SMs and the data concentrator is based on the standard EN 13757-5 that implements a radio mesh topology. Moreover, they are IEC 62056 compliant, the latter being the international standard of the DLMS/COSEM specification (Device Language Message Specification/Companion Specification for Energy Metering). The models of Smart Meters used for this application, belonging to the Kamstrup OMNIA suite, are compliant with international standards. They measure active positive energy (EN 50470-1 and EN 50470-3), reactive energy, and active negative energy (IEC 62052-11, IEC 62053-21 and IEC 62053-23), as well as Power Quality features according to EN 50160 [50].

Once the consumption data are available on the Data hub, the retailer takes them and records them on the BC. In this way, all parties are sure that the recorded consumption data have not been modified by untrusted users before being sent to the BC. In any case, customers can verify the authenticity of the data using the local channel.

### 3) ACTORS OF THE DR SERVICE

The participation of consumers/producers in the DR service takes place through their aggregation in virtual units, which are constituted and managed by a subject known as Aggregator or BSP. According to the European energy efficiency directive (2012/27/EU), the Aggregator is defined as: "a DR service provider that combines multiple short-duration consumer loads for sale or auction in organized energy markets". The Aggregator has the responsibility to respond to the modulation orders given by the Transmission System Operator, TSO, in order to avoid any unbalance of load on the grid that can occur at certain times of the day when the energy supply does not meet the demand (see Fig. 6) [51], [52].

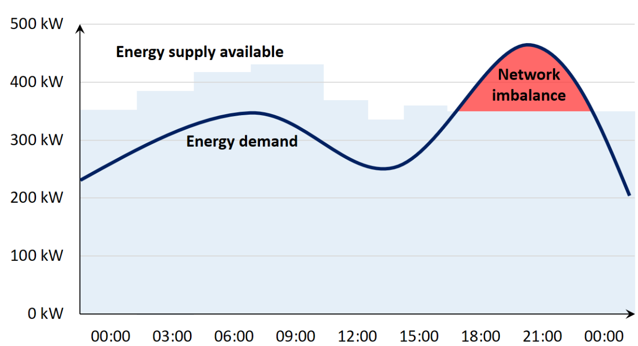



**FIGURE 6.** Mismatch between supply and demand.

The Aggregator responds to these orders by requesting, in compliance with the constraints and requirements necessary for the aggregate resources, the modulation of the load from consumers that make up the virtual load unit. The term Aggregator usually refers only to the consumer manager, but at the same time, this entity can also manage multiple generators or storage units [53].

In the literature, there are different business models underlying aggregation [51], [53], [54], but not all of them are actually applicable.

With the proposed BC-based framework, it is possible to remove actors like the Aggregator from the energy sector, since the aggregation in virtual units of consumers/producers is done through the BC. In this way, the grid operator can communicate the DR request directly to customers and the BC will remunerate them based on the service provided following the request, generating a new business model for aggregation.

### B. BASELINE CALCULATION METHODOLOGY

The last step of a DR event consists in the remuneration of the customers who have responded positively to the request to modify the load as communicated by the Aggregator or, as in this case, by the DSO. In order to measure the load modification of the customer, it is necessary the identification of a "Customer Baseline Load" (CBL). The CBL is the reference consumption of each customer that participates to the DR program and is used to assess the effects of the DR on a given customer or a set of customers load profile. In fact, the DR effect can be quantified as the difference between the consumption during the DR event and the CBL (see Fig. 7). In the implementation of a DR program, the estimation of the CBL is fundamental, because the difference between the CBL and the actual consumption represents the customers' performance under the DR program and is the reference to design the economic compensation mechanism. In the literature, there are many methods to evaluate it [55]–[60], but not all of them can be used efficiently in a DR program because they are too complicated.

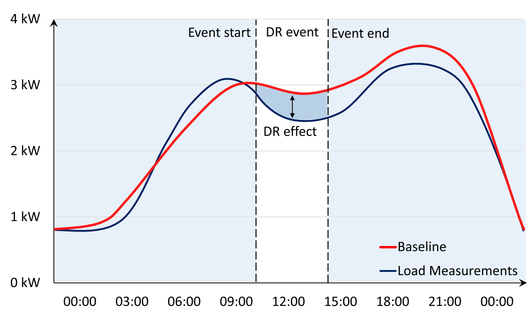



**FIGURE 7.** Comparison of baseline with the performed load profile during the DR event.

The work in [59] also classifies CBL evaluation methods into three general categories:

1) *Averaging methods*: based on the hypothesis that the load profiles of an individual customer in adjacent several days are similar, thus, the CBL can be simply estimated based on the average load of days prior to the event day;
2) *Regression methods*: try to fit a linear function to describe the relationship between the load and explanatory variables such as historical load and weather data (e.g. temperature, humidity and wind speed) and then use this function to estimate the CBL of the event days;
3) *Machine Learning methods*: try to find the potential relation between the load and its impact factors. Unlike regression models, Machine Learning (ML) methods can find the hidden non-linear relation and exhibit high levels of estimation accuracy.

The methods of calculating CBL, especially when these are parts of a shared mechanism, are required to be simple, transparent, and easy to understand for both utilities and customers. Hence, although ML methods may deliver higher estimation accuracy, they are difficult to be applied in practice due to their inherent limited transparency.

The North American Energy Standards Board (NAESB), an industry forum for the development and promotion of standards in wholesale and retail gas and electricity markets, developed a set of common definitions and practices defining five types of baseline evaluation methodologies and the suitability of each method for each type of service provided by the DR service [61].

For this work, we used two averaging methods:

1) *"HighXofY"* for the baseline during the weekdays [57];
2) *"LowXofY"* for the baseline during the weekend [58].

According with the NAESB definitions these two methods are both within the *"Baseline Type-I"* evaluation methods category. According to NAESB, the performances of Baselines Type-I are suitable for service in which Demand Resources are compensated based solely on Demand reduction performance, as in the present case. Moreover, the two methods used are well suited for implementation in SC, as they are simple, easy to understand and deterministic.

For each customer, the SC evaluates a CBL consisting of two vectors of typical power consumption in 24 hours during the weekdays ($\mathbf{B}^{(c)}_{\mathrm{wd}}$) and the weekends ($\mathbf{B}^{(c)}_{\mathrm{we}}$), whose general expression is given below in (1).

$$\mathbf{B}^{(c)} = \left[\bar{P}^{(c)}_{B,1}, \bar{P}^{(c)}_{B,2}, \ldots, \bar{P}^{(c)}_{B,h}, \ldots, \bar{P}^{(c)}_{B,24}\right] \quad (1)$$

The horizontal bar above the symbols of power consumption $\bar{P}^{(c)}_{B,h}$ indicates that load values related to a specific hour $h$ of the day $d$ are dynamically averaged over multiple days according to:

$$\bar{P}^{(c)}_{B,h} = \frac{1}{X} \sum_{j \in \mathrm{High}(X,Y,d)} P^{(c)}_{B,h,j} \quad \forall\, h \in \{1, 2 \ldots, 24\} \quad (2)$$

for the weekdays baseline, and

$$\bar{P}^{(c)}_{B,h} = \frac{1}{X} \sum_{j \in \mathrm{Low}(X,Y,d)} P^{(c)}_{B,h,j} \quad \forall\, h \in \{1, 2 \ldots, 24\} \quad (3)$$

for the weekend baseline.

The left term in (2) and (3) is the value of the baseline at hour $h$ by averaging the power of the $X$ days with the highest consumption (2), or the lowest consumption (3), within the $Y$ non-DR days preceding the day $d$, that is day on which the DR event is notified to customers, which is assumed as the day before the DR event.

Both for weekdays and for weekends, this averaging methodologies work on the same set of the $Y$ days that do not include DR or curtailment programs. The baselines are evaluated over the $Y$ preceding days, on which the *HighXofY* method was applied for the weekdays baseline, and the *LowXofY* method for the weekend baseline. Finally, the sliding window over the last $Y$ days permits to take into account seasonality.

### C. REWARD MECHANISM

In all DR programs described above, customers are expected to reduce or increase their load, but what changes between programs is how customers respond to demand and especially how they are remunerated for the service provided.

Currently, in the management of DR events, the system operator communicates to the Aggregator or BSP the request for load modulation in a given area of the electrical system. The participation of customers in the DR programs is regulated by a contract with the Aggregator which establishes an incentive for the customer if he/she is able to meet the request and the payment of penalties when the request is ignored. The Aggregator, knowing the total capacity of the customers of that area who have decided to participate in the DR service, responds to these orders by requesting, in compliance with the constraints and requirements necessary for the aggregated resources, the modulation of the load to the customers that make up the virtual load unit [52]. Usually, through an auction between the system operator and the Aggregator, the power reduction/increase and the price that the system operator will pay to the Aggregator for the service is determined. At the end of the DR event, the Aggregator remunerates the customers of that virtual unit according to the designed DR program [23]. It is clear that this system, suffers from a lack of transparency towards the end users.

In this work, the aggregation in virtual units of consumers/producers is done through the BC. So, the system operator can communicate the DR request directly to customers and at the end of the DR event the SC will remunerate them based on the load variation provided in response to the request. The day in which the DR service takes place, the customer's consumption is recorded by the SM and is written by the retailer on the BC. At the end of the day, the SC assigns each customer a remuneration based on the load adaptation with respect the baseline following DR's request.

Customers' remuneration is an important aspect of DR programs. Some of the remuneration methods present in the literature provide a constant reward for each unity of energy consumption that has been modified by the customer, others consider the remuneration as a function of the change in the customer's profile [52], with the time of the day (as in Time-of-use schemes) or with the kind of customer. As an example, in [62] the authors consider different remunerations for five categories of customers, while in [63] the authors propose a remuneration scheme that considers an incentive price dependent on the customer's power changes following a DR program, and the differences between the amount of power purchased by the Utility on the Spot market and the retail price for customers, so as to limit the loss for the Utility.

In this paper, a remuneration mechanism based on the variation of power over baseline using a quadratic remuneration function is used. The latter is usually adopted for economical evaluations in the electric energy field [64], and for the DR event is expressed as follows:

$$r = \sum_{h=1}^{24} \mathcal{H}(\bar{P}_{B,h} - P_h) \cdot (\bar{P}_{B,h} - P_h)^2 \tag{4}$$

where $\mathcal{H}$ is the Heaviside function; it is 1 when the argument is positive, and 0 otherwise, permitting to remunerate only load reductions and neglecting load increments. In (4), $\bar{P}_{B,h}$ is the baseline value at hour $h$, $P_h$ is the measured load profile at hour $h$ and their difference is representative of customer response during the DR event. In our experiments, the operator requests load reductions and only those consumers that reduce their load will receive a reward, according to a parabolic law.

The remuneration is given to users in utility tokens [65] here called DRtokens. Utility tokens holders can have access to a current or prospective product or service but the possession of utility tokens does not grant holders rights that are the same as those granted by investments. However, the value in terms of access to products or services of such token is out of the scope of this paper.

### D. IMPLEMENTATION OF THE DR PROGRAM THROUGH A PURPOSE-DEVELOPED SMART CONTRACT

In our experiment, the power network is a microgrid supplying consumers, while the BC network consists of a node owned by the system operator, one by the retailer and two by the customers (see Fig. 4).

As already explained, the aggregation of the customers in virtual units is done through the BC, so the system operator can communicate directly to the customers the request of load adaptation in order to avoid a congestion on the network in certain hours of the day, for example. The proposed application runs through the SC a capacity/incentive-based DR program applied at residential level implemented using a Load Response program. Therefore, it was assumed that customers participate in the program by making their load capacity available. The test scenarios have been developed considering that customers may choose to shift some loads in response to the DR event in order to reduce the total load on the grid during the period when the peak load is expected. When the system operator communicates a DR event, the SC running on the peers distributes the total load reduction to the customers proportionally to their own baseline.

```
func (t*SmartContract) Invoke(stub
    shim.ChaincodeStubInterface)pb.Response{
    function, args:=stub.GetFunctionAnd
    Parameters()
    fmt.Println("invoke␣is␣running"
    +function)

    if function=="recordEnergy"{
        return t.recordEnergy(stub,args)
    }else if function=="evaluateBaseline"{
        return t.evaluateBaseline(stub,args)
    }else if function=="notifyDRevent"{
        return t.notifyDRevent(stub,args)
    }else if function=="queryLoadReduc"{
        return t.queryLoadReduc(stub,args)
    }else if function=="getDRToken"{
        return t.getDRToken(stub, args)
    }else if function=="queryEarnedToken" {
        return t.queryEarnedToken(stub,args)
    }
    fmt.Println("invoke␣did␣not␣find␣func:"
    + function)
    return shim.Error("Received␣unknown
␣␣␣␣function␣invocation")
}
```

**Listing. 1. Main DR SC functions.**

The customers respond to the request by shifting some loads during the DR period in order to better satisfy the request and to receive the maximum remuneration.

The SC represents the main element of this BC-based system, because it is the network component that allows to implement the logic of each kind of transaction, to execute the above-mentioned DR program and verify the integrity of each transaction sent by the network users. The SC is installed on each peer, and each time a user submits a transaction proposal over the network, this transaction proposal is processes by the SC of all peers, then the App Client of the users who submitted the transaction receives the responses to the transaction proposals from the SC of all the peers and compares the correspondence of the responses obtained. If the responses received are consistent it means that the submitted transaction is compliant with the logic implemented by the SC and that all peers have verified this consistency, so the App Client can send the response within a transaction message to the Orderer who inserts it into a new block and sends it to all peers who update the ledger. Using the SC a distributed consensus on transactions consistency is achieved. The SC was developed by using the general programming language "Golang" (Go). All transactions are processed by invoking properly structured SC functions. Listing 1 shows the SC entry point for the main functions invocation. In the next section is described how these functions are used and invoked by the Apps Client of the various network users in order to perform a DR event.

## IV. LABORATORY TESTS

This section describes the results obtained by implementing the proposed architecture using a hardware testbed for the emulation of the domestic power profiles. It also describes how this emulated scenario integrates with the metering architecture, as well as with the BC network.

### A. EXPERIMENTAL SETUP

To validate the proposed solution a hardware testbed was assembled for emulating the power installation and the behaviour of domestic consumers. The setup allowed us to implement two households equipped with both shiftable and non-shiftable loads. Moreover, they are interfaced with the grid via SMs that record the aggregated power. These tests were carried out at the Microgrid laboratory of the Department of Energy Technology at Aalborg University.

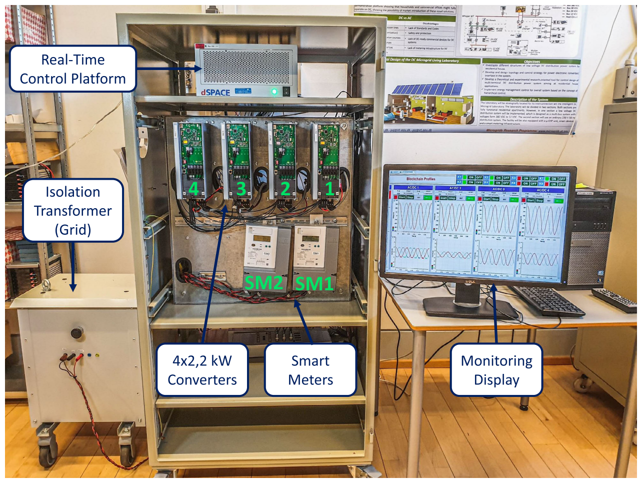



**FIGURE 8. Experimental testbed emulating two residential consumers.**

The experimental setup is shown in Fig. 8. It consists of four bi-directional DC/AC converters, which operate in grid-connected mode and whose power references are fully controllable. The unit responsible for the real-time control and pulses generation for the inverters is the real-time control platform dSPACE shown on the top of the setup. This system implements the primary control, PLL and power control loops for each inverter independently. Moreover, it also enables wireless control of the power references via an MQTT interface and provides local monitoring capabilities of voltage and current waveforms. The dSPACE platform was programmed using MATLAB/Simulink, where the corresponding primary control loops, PLLs and power control loops were developed and compiled, before being deployed into the system. The monitoring platform is associated with the ControlDesk dSPACE software which is just used to supervise the proper operation of the system. The testbed includes two SMs, one for each simulated household, and an isolation transformer for the grid connection. A detailed diagram of the complete architecture is provided in Fig. 9.

On the top part, the power electronic system in the setup for one household is shown. The inverters are supplied by a DC power source. In the AC output, an LCL filter is used to reduce the harmonic content of the generated waveforms. From each pair of inverters, one is used for emulating the non-shiftable component of the load profile, while the other

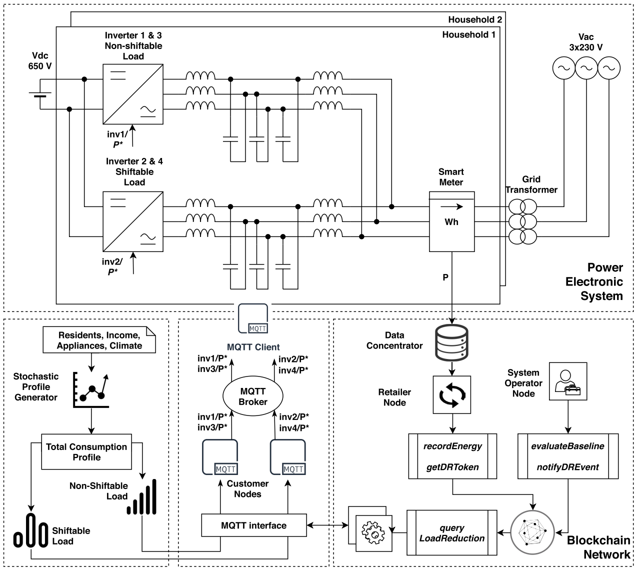



**FIGURE 9.** Conceptual diagram of the inverters connection for one customer, BC network and SM architecture.

is used for the shiftable loads. Both of them are finally connected to the same point downstream the LCL filter and subsequently, to a common SM that measures the total consumption of the house. It should be noted here, that the SM has been installed with its terminals inverted, so a power injection into the grid is considered as consumed energy by the emulated households.

Following the architecture showed in Fig. 4, four peer nodes were deployed together with the hardware setup and the SM infrastructure to form a BC network as illustrated in the box at the bottom right of Fig. 9: a system operator node and a retailer node on one PC and two customer nodes on another PC. A copy of the DR SC and a set of specifically developed client Apps were also installed on each node with the aim of allowing every user on the network to interact with the BC. To keep the system as generic as possible, and ease the integration with third-party solutions, the client Apps were conceived as RESTful web services with communicate on the back-end with the BC network. These apps were implemented using the general programming language Node.js. The client apps and the main functions used to interact with the BC network are shown also in Fig. 9.

The role of the system or grid operator is to manage the identities of the retailers, trigger the baseline calculations (*evaluateBaseline*) and execute DR events (*notifyDREvent*). Therefore, the system operator app provides a RESTful interface for registering retailers into the BC network. It also implements a module for periodically triggering the calculation of the baseline, which is performed at the end of each day. Finally, another RESTful service is used for posting DR events, where the system operator specifies the start time, the end time and the requested load reduction.

The retailer manages the customers' identities and is responsible for uploading customer consumption data on the BC (*recordEnergy*), taking them from the data concentrator. It also triggers the SC function to generate the tokens for the participation in DR programs (*getDRToken*). The retailer app provides three functionalities: (i) a RESTful service for the registration of customers, (ii) a periodic module for reading the SM measurements and recording them into the BC every day, and (iii) a periodic module to trigger the evaluation of DR tokens for the customers when DR events are implemented.

Finally, the customer nodes are just responsible for reading the load reduction established by the system operator after triggering a DR event (*queryLoadReduction*) and its implementation using the available shiftable loads. Therefore, the customer app periodically checks if a DR event has been triggered for a given day and arranges the shiftable part of the load profile accordingly. This modification is performed by means of interacting with the MQTT interface which sends the consumption profiles to the inverters for the emulation.

Every time a network user through the app invokes a SC function to execute a transaction, the transaction information is diffused between the BC network peers through the so-called "gossip data dissemination protocol" [66]. Peers use this protocol to transmit information on the communication channel in a scalable way. Gossip messaging is continuous and each peer on a channel constantly receives current and consistent data from multiple peers. Each gossip message is signed, allowing participants sending false messages to be easily identified. Peers affected by delays, network partitions or other causes causing missed blocks will eventually be synchronised with the current ledger status by contacting the peers having these missing blocks. This communication protocol based on the division of the workload for the execution of transactions makes it possible to optimise the performance of the BC network in terms of security and scalability:

- it allows to manage the identification of peers and their membership in the channel, continuously detecting available and offline peers;
- diffuses the data of the ledger through all the peers of a channel allowing the synchronisation of data to those peers that have missing blocks;
- updates the newly connected peers very quickly on the changes that occurred to the ledger during their disconnection.

To generate the aforementioned household power profiles a previously developed stochastic model for the generation of residential loads was used [67]. This model provides appliance disaggregated 1-minute resolution data for a given household with a set of appliances, residents, income level, and surrounding climate characteristics, which determines the behaviour of the users. The appliances are allocated based on the ownership probability. Among them, in the non-shiftable part, we can find refrigerators, televisions, laptops, pc, stoves, microwaves, oven, iron, coffee maker, toaster, water heater, etc. On the other hand, only washing machines, dryers and dishwashers are considered as shiftable loads.

### B. OPERATIONAL WORKFLOW OF APPLYING THE BC TECHNOLOGY FOR A DR PROGRAM TEST IN A LABORATORY ENVIRONMENT

Before performing the DR event, it is needed to set the BC network. Once Hyperledger Fabric is installed on all the peer nodes, the next step is to generate the digital identities of the users that will participate in the network. The developed network consists of two organizations, which are part of the so-called "DRconsortium". The MSP of the system operator manages the identity of the retailer (Org1), while the MSP of the retailer manages the identities of the customers (Org2). The identities are comprised of X.509 digital certificates, which are distributed to each user. Subsequently, a communication channel is created between the peer nodes, where they all can authenticate with their respective identities. At this point, the SC is installed on each peer and the BC network is ready to work. From this point on, the following operation is assumed in the network. In our application, two roles are considered, the system operator, which requests the DR service for balancing the network, and the energy retailer that provides services to the users. In other context, however, both entities can be unified in the DSO.

1) *Every day*, the retailer sends the customers' load profiles to the BC through the SC, taking them from the DSO data hub. In addition, the system operator triggers the SC to evaluate the baselines of the customers;
2) *The day before DR event*, the system operator notifies the BC network about the day, time window and total load reduction, which is distributed by the SC to the customers according to their estimated baselines;
3) *The day of the DR event*, the customers read from the BC the desired load reduction evaluated by the SC in order to satisfy the system operator's request. Their actual consumption for that day is also recorded as stated in point 1;
4) *The day after the DR event*, the retailer triggers the SC for customer' remuneration with the aforementioned utility tokens. We assumed that the SC assigns them only if customers' consumption during the DR event is compliant with the desired load reduction, ignoring the possible penalties if the consumption is not compliant.

A total time horizon of 36 days was considered for implementing the experiment. Since generating 36 days of load profiles using directly the hardware setup implies an unnecessary time-consuming process the experiment was divided into three phases:

1) *Pre-allocation*: First, 33 days of load profiles were directly recorded into the BC with the same resolution of the smart meter (15 minutes).
2) *Normal behaviour emulation*: Subsequently, 2 days of normal consumption profiles for the two households were emulated using the previously described testbed. In order to downscale the time of the experiment by a factor of 3 (8 hours needed to simulate 24 hours), the SMs were configured to record the average power every 5 minutes, while the power references for the inverters generated by the model with 1-minute resolution were updated with a frequency of 20 seconds. In addition, a time adjustment routine was included in the retailer client app so the 5-minute resolution data read from the SMs were transformed into 15-min resolution data due to the downsizing.
3) *DR event emulation*: In the last day, the system emulated a DR event created by the system operator. The customers respond accordingly by moving the shiftable loads to the requested reduced period. This is done by the customer app client interacting with the MQTT interface which sends the power profiles, so the shiftable appliances profiles are reallocated.

To automate all of this process, a MATLAB script was created. This script communicates with the four Client Apps of each node, namely, system operator, retailer and clients (1 & 2) using the MATLAB RESTful web services functions webread and webwrite. In addition, the MQTT library was employed to periodically update the references of the power profiles during fases 2 and 3.

### C. TEST OF THE PHYSICAL SETUP FOR RECORDING THE POWER PROFILES INTO THE BC

As a first step, the system must record the consumption profiles making use of the SM infrastructure, which is accessed by the retailer node. In our scenario, after the 33 days of preallocation, this method is used for the two days of normal behaviour (days 34th and 35th) and the day of the DR event (day 36th). Since the behaviour of the power system is the same for both normal and DR days, a 24-hour profile of household 1 for a normal day is presented in Fig. 10.

As can be seen in fig. 10(a) the consumption profile is divided into two components which are sent as power references to a pair of inverters (1 and 2 for household 1, and 3 and 4 for household 2). The first inverter (Inv 1) generates the non-shiftable component of the household consumption profile, while the second inverter (Inv 2) is responsible for emulating the shiftable component of the load.

Following the power electronic system architecture presented in Fig. 9, the output of each pair of inverters is connected to a common SM meter and subsequently to a common point of coupling with the grid. Therefore, the SM is only able to measure aggregated consumption (shiftable and non-shiftable components). Moreover, while the resolution of the power profiles sent to the inverters is 1 minute, the SM takes 15-minute resolution average power samples at the output of the system.

Fig. 10(b) shows a comparison between the expected aggregated consumption inverters 1 and 2 and the actual power profile recorded by SM 1 for day 34th, which was obtained by the retailer client application by accessing the DSO data hub and subsequently inserted in the BC network. It can be observed how the power recorded by the SM totally matches expected set points, although with a lower resolution.

Regarding the quality of the emulation, the average absolute error between the expected and the recorded profiles

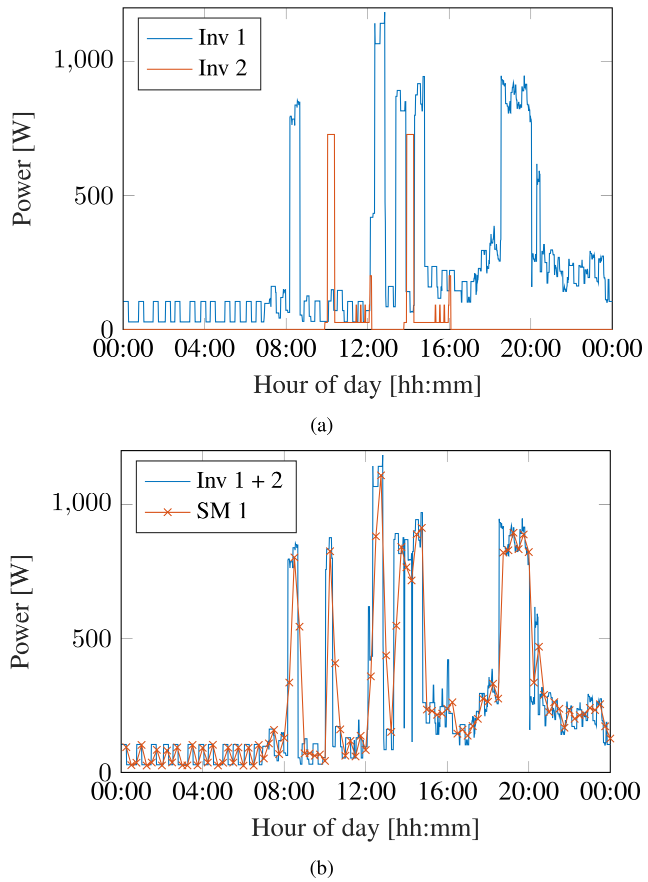



**FIGURE 10.** **Profiles sent to inverters and recorded by SM into the BC network, for non-shiftable & shiftable loads (a) and total profile (b).**

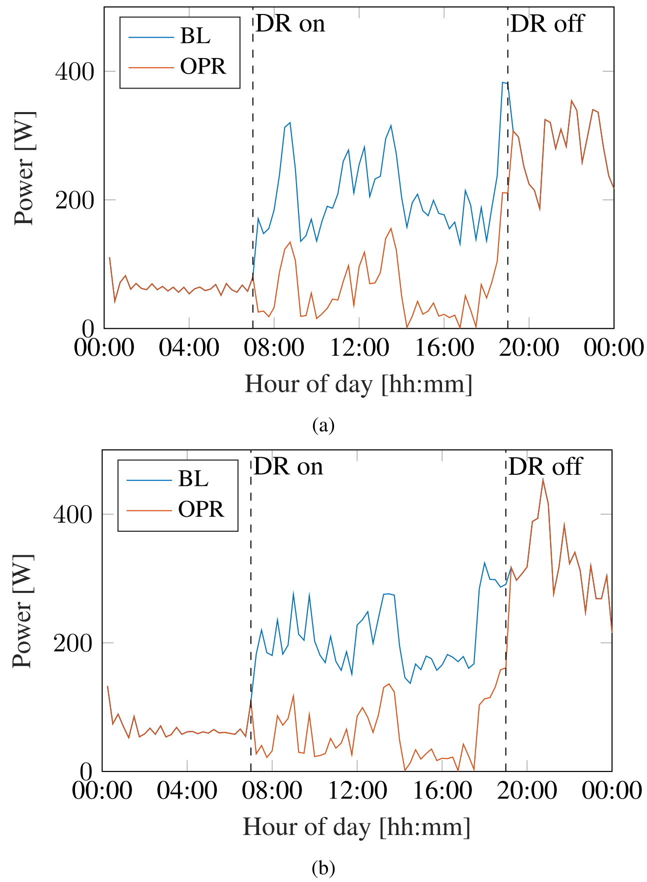



**FIGURE 11.** **Baseline calculations for day 35th and OPR for the following day with DR event for household 1 (a) and household 2 (b).**

for the 24 hours test was approximately 10 W. Moreover, the total daily energy consumption was around 1% lower than expected. These errors are probably a result of power losses in the system. Each inverter controls its output power after the LCL filter to compensate for passive losses, yet the use of a common AC/DC source and the parallel connection of the inverters can lead to small circulating currents. These could be avoided by using, for instance, individual isolation transformers, nevertheless, their impact is so small in our scenario that no measure was taken.

### *D. BASELINE AND OPTIMAL POWER REDUCTION CALCULATIONS*

After the 35th day, the system operator decides to trigger a DR event in the system. Therefore, a power reduction of 300 W per 15-minute average from 07:00 h to 19:00 h is requested. At this point, 35 daily power profiles for each household have been recorded on the BC and the baseline is recalculated with the new information. These baselines were evaluated by the SC using (2) and (3) considering Y=35, X=21 for the weekdays and X=14 for the weekend baseline.

The day in particular for the considered DR event is a weekday. Fig. 11 shows the calculated baseline (BL), as well as the optimal power reduction (OPR) obtained for each household. It can be observed, that both baselines differ between them since each household has its particular behavioural patterns. For instance, it can be seen that although the demand peaks occur around the same time for both consumers, the household 2 has a higher demand peak during the evening than household 1, while household 1 has a higher power consumption during the central hours.

Therefore, the OPR algorithm in the SC takes into account this, to proportionally distribute the requested reduction between the two customers. This is illustrated in Fig. 12

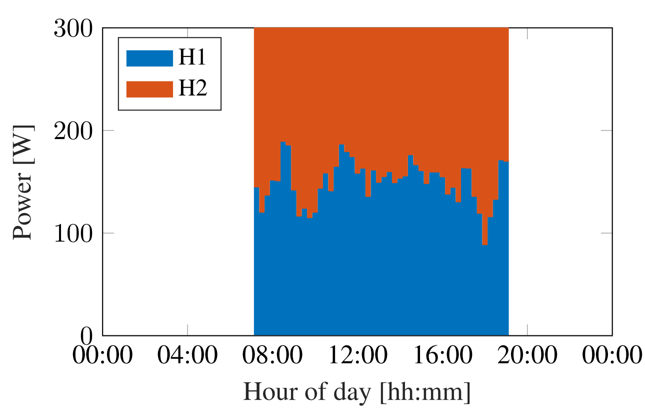
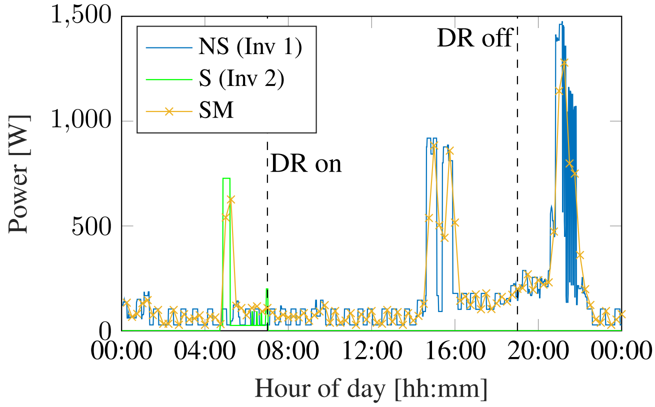
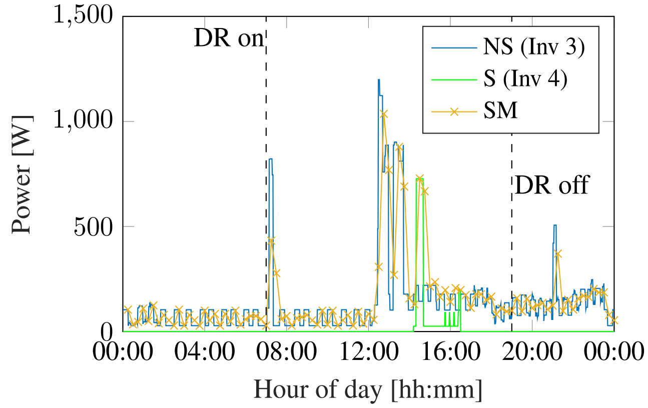


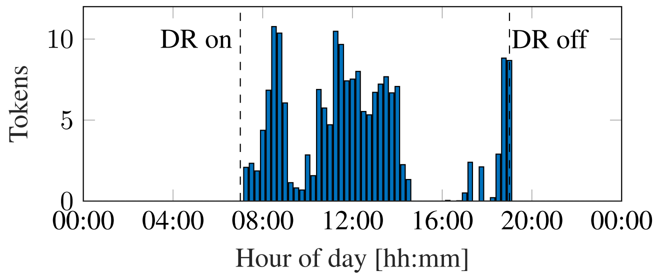

**FIGURE 12.** **Proportional reduction requested to each household.**



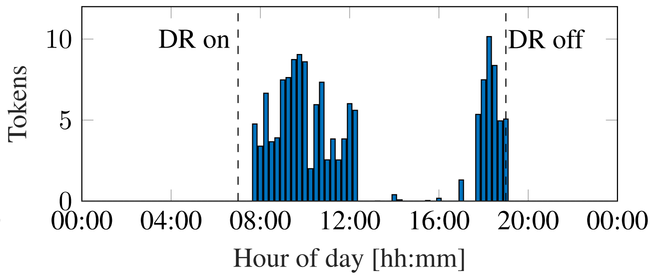

(a) Household 1. Non-shiftable (NS) and shiftable (S) profiles sent to the inverters for the DR day and the records of the SM.




(b) Household 2. Non-shiftable (NS) and shiftable (S) profiles sent to the inverters for the DR day and the records of the SM.




(c) Household 1. Number of tokens awarded for the DR response in 15-minutes intervals.




(d) Household 2. Number of tokens awarded for the DR response in 15-minutes intervals

**FIGURE 13. Response of the user to the DR event and rewards given after the day.**

where the 300 W reduction is allocated every 15 minutes for household 1 (blue bars) and household 2 (orange bars).

### *E. DR EVENT CERTIFICATION AND REWARD SYSTEM*

The previous subsection has described how the OPR is generated for each household. Finally, in this section, the behaviour of the user during the DR event day and its consequences are evaluated. Fig. 13 shows the consumption profiles of both households, distinguishing non-shiftable and shiftable loads, as well as the aggregated samples taken by the SMs. For a more interesting test case, only household 1 is considered to fulfil the DR event. In Fig. 13(a) and (b), the green line represents the shiftable consumption. Household 1 has reallocated the shiftable loads to the periods before the DR event trigger to comply with the required power reduction. On the other hand, the shiftable loads in household 2 are used during the DR event. This leads to different rewards for each user as depicted in Fig. 13(c) and (d), which represents the 15-minute tokens awarded to each users following (4). Household 1 was able to keep its consumption low for almost all the DR period so in total 188 tokens were awarded to Household 1. Household 2, however, incurred a high consumption for more hours as compared to Household 1, so the reward was only 147 tokens.

It should be observed at this point, that even though a power reduction was asked by the system operators, both users have high consumption during the DR event. However, this was expected as the flexibility in this scenario is limited to shiftable loads. This means that the system operator should also consider this issue, and what are the possibilities for the users for setting realistic power reduction periods and figures. Future implementations will consider the implementation of more advanced DR scenarios considering the control of thermal loads or energy storage systems (ESS).

### *F. EXPERIMENTAL NETWORK PERFORMANCE*

In public or permissionless BC, like Bitcoin, anyone can join the network and execute a transaction. In Bitcoin, due to Proof of Work (PoW) based consensus, a creation time of 1 block each 10 minutes and a fixed block size of 1 MB is considered. The peak throughput of transaction processing is between 3.3 and 7 transactions per second. The confirmation of six blocks takes about one hour. Ethereum uses a PoW-based consensus that can process about 25 transactions per second.

In private or permissioned BC, such as Hyperledger Fabric, the generation time of one block is shorter, thanks to simpler consensus processes based on faster and less computationally intensive algorithms. In Hyperledger Fabric, transaction messages are sent to the Order service. The Orderer then receives the transactions on that channel and queues the messages. The Originator creates a new transaction block per channel and delivers the block to all peers via the aforementioned gossip protocol. The gossip protocol connects the peers in the channel and transmits the channel logs and data in a scalable way. In the public Bitcoin BC, all transactions are handled through a series of sequential operations in blocks and are added to the ledger. This sequential process will not gain performance benefit when using more powerful hardware. In Hyperledger Fabric, the consensus is carried out by the Ordering service, which is designed in a modular and fully connectable way. There is the possibility to select scalable consent mechanisms (Solo, Kafka and Bizantine Fault Tolerant) for application use cases. The Ordering service, which can be set up as a cluster of Orderer nodes, process messages, ensuring that each Ordering process receives transactions and generates blocks in the same order. This event-driven synchronization design ensures better performance than that of the public BC.

The significant parameters of ''configtx.yaml'', are indicated in Table 1, to modify some parameters to improve the performance:

**TABLE 1.** **Used parameters and execution time of SC function for the experimental tests.**

| BC Parameter | Value |
|---|---|
| *BatchTimeout* | 2 s |
| *MaxMessageCount* | 10 |
| *AbsoluteMaxBytes* | 99 MB |
| *PreferredMaxBytes* | 512 kB |
| **SC function** | **Average execution time [s]** |
| *recordEnergy* | 10.2 per load profile (96 energy values) |
| *queryLoadProfile* | 0.065 |
| *evaluateBaseline* | 12 per customer considering 35 days |
| *queryBaseline* | 0.065 |
| *notifyDRevent* | 2.3 |
| *queryLoadReduction* | 0.065 |
| *getDRToken* | 2.3 |
| *queryEarnedToken* | 0.065 |

- *BatchTimeout*, defines the time to wait before creating a new block;
- *MaxMessageCount*, defines the maximum number of transactions to be inserted in a block during the batch time;
- *AbsoluteMaxBytes*, defines the absolute maximum number of bytes allowed for transactions serialized during a batch time;
- *PreferredMaxBytes*, defines the maximum number of bytes allowed in a batch. A transaction larger than the preferred maximum bytes will result in a batch larger than the preferred max bytes.

To achieve higher throughput, it is possible to increase *MaxMessageCount*, but as more computational power is required, the block size gets larger and more bandwidth is needed. In general, by changing the parameters in configtx.yaml it is possible to optimize the transaction throughput, but this differs from case to case depending on the application. In this application, the authors used the default parameters indicated in Table 1. In this way, the maximum number of transactions per second is 25, that is 50 transactions per batch time. Considering the scenario discussed above, and that the network was implemented using the internal telecommunication network of the Microgrid Laboratoy (with very low latency), the following Table 1 shows the time required for each type of transaction or query executed by invoking the different functions of the DR smart contract.

With regard to memory consumption, it has been estimated that the size in bytes of a transaction for the recording of a power value or DRtoken of a customer is 5 kB, so one block consisting of 10 transactions has a size slightly greater than 50 kB (51.2), while the size of a transaction for recording the baseline, or a DR event, is 10 kB. In general, for the tests executed in this work, the memory consumption can be considered negligible, but considering a real scenario, with hundred of thousands of end users, the size of the chain could become not negligible. In this case, clients with not enough storage capacity could participate to the BC as 'light clients', i.e. installing only the App client, invoking the SC and accessing the ledger on the nearest peer.

## V. CONCLUSION

In this paper, a novel methodology for the certification and remuneration of the DR service is proposed and tested. The method relies on customer baseline calculation and registration, on DR events metering and registration and on a remuneration scheme carried out by a newly developed Smart Contract. A laboratory experiment has been carried out for validating the methodology in a realistic testbed. The experiment is described in details in the paper. The test uses inverters for emulating real loads, smart meters for getting data of power consumption, an open-source BC platform, and new SCs. The BC is a flexible and powerful tool that may suffer of timing and scalability issues. This paper experimentally validates the use of a DR solution based on Hyperledger Fabric and demonstrates that it suits the needs of DR programs and the timing for handling data with the BC is compatible with the timing of DR events. The proposed solution uses the BC as a multipurpose tool for handling messages and data among the actors providing transparency and security, for computing customers' load baselines, for enforcing the load reductions and finally, for remunerating customers according to their contribution. The experiments demonstrate that all the above indicated goals can be achieved while preserving customers' privacy, by using the Hyperledger Fabric communication channels both for data and for the SC computation.

A simple remuneration scheme was considered as well as a customer baseline calculation algorithm. Both were implemented in suitable SC. Identities and personal data were protected using tools available for Hyperledger Fabric platform. Future tests will consider more customers to check the scalability of the proposed solution for what concerns different consensus protocols and the application of new algorithms for CBL estimation and remuneration functions.

Since the main challenges of using blockchain technology reside in latency and thus limited scalability as well as power consumption, future tests will consider more customers to check the scalability of the proposed solution, as well as different technologies for peripheral devices to check power consumptions and timing in all scenarios. On the setup created on purpose, different consensus protocols and new algorithms for CBL estimation and remuneration functions will also be tested. Besides, further work will be aimed at identifying the way utility tokens can be negotiated against services offered and what services are more suitable to be offered in this scheme (discounts on bills, discounts for buying behind the meter storage, etc..).

The data concentrator, which has been used for getting measurements from multiple meters is compliant with an IoT scheme operated by the energy distributor. In the future, the removal of the negative side of having a data concentrator will be considered, by the implementation of suitable compensation measures at the customers' premises.

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